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# Advanced Micro Ring Resonator Filter Technology

*G. Lenz and C. K. Madsen*  
*Lucent Technologies, Bell Labs*

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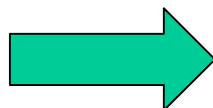
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# All-Pass Filters

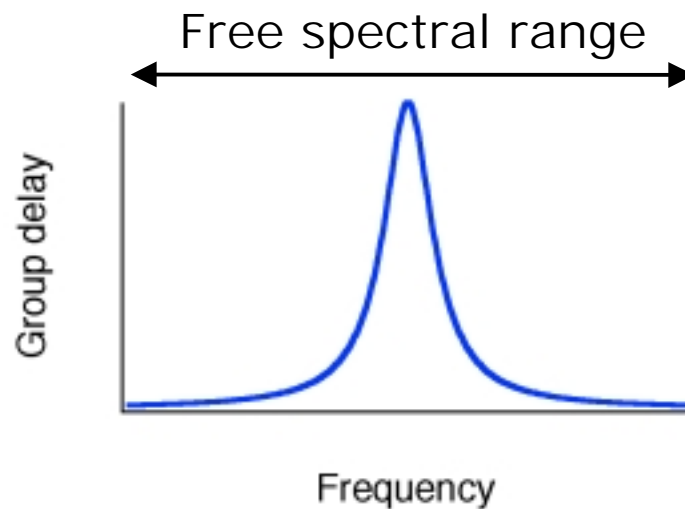
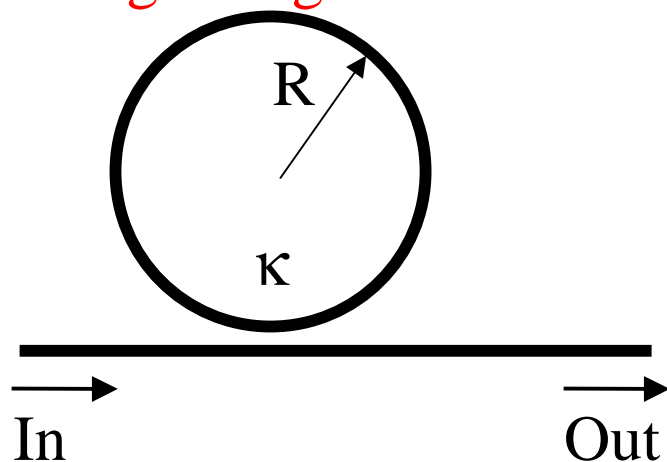
$$|H(\omega)| = 1$$

$$\phi(\omega) = \text{arbitrary}$$



- ◆ Phase equalization
- ◆ Dispersion compensation
- ◆ Optical delay line

Single stage APF



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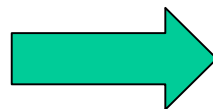


# Mathematical Form

$$H(\omega) = \prod_{n=0}^{N-1} \frac{e^{j\omega} - z_n}{e^{j\omega} z_n^* - 1} = \prod_{n=0}^{N-1} \frac{e^{j\omega} - r_n e^{j\theta_n}}{e^{j\omega} r_n e^{-j\theta_n} - 1}$$

$$|H(\omega)| = 1$$

$$\phi(\omega) = \sum_{n=0}^{N-1} \text{Arg} \left[ \frac{e^{j\omega} - z_n}{e^{j\omega} z_n^* - 1} \right]$$



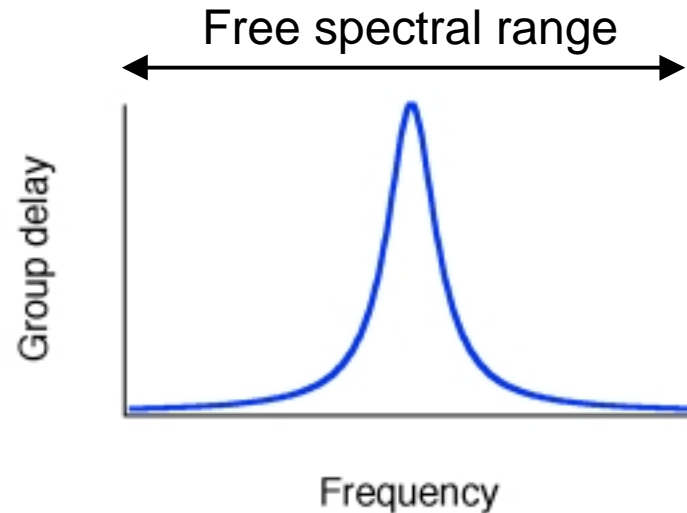
Phase equalization without  
amplitude distortion



# Group Delay

$$\tau(\omega) = \sum_{n=0}^{N-1} \frac{\sinh \chi_n}{\cosh \chi_n - \cos(\omega - \theta_n)}$$

$$\chi_n = \ln r_n$$



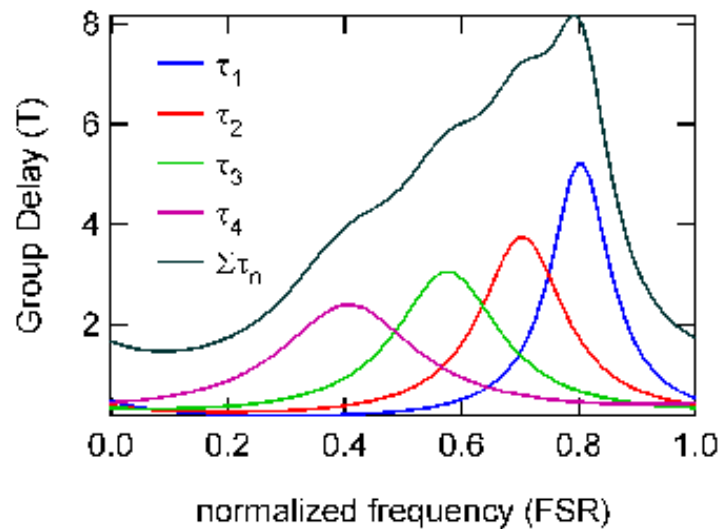
$$D(\omega) = \frac{d\tau(\omega)}{d\omega} \propto \frac{1}{FSR^2}$$

Larger FSR  $\Rightarrow$  smaller dispersion; More stages  $\Rightarrow$  more dispersion

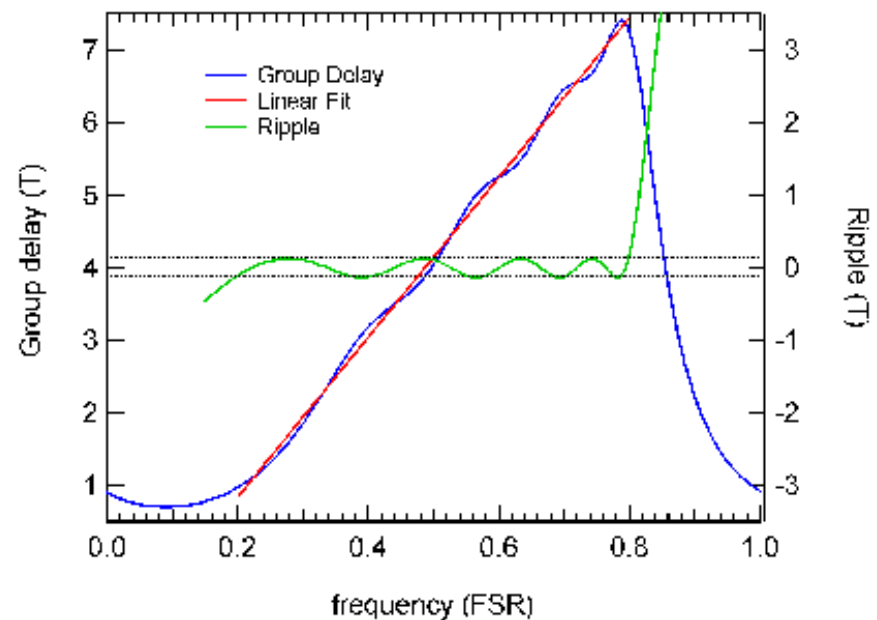


# Four-Stage All-Pass Filter

*Approximation of  
Linear group delay  
across pass band*



*Equi-ripple design*

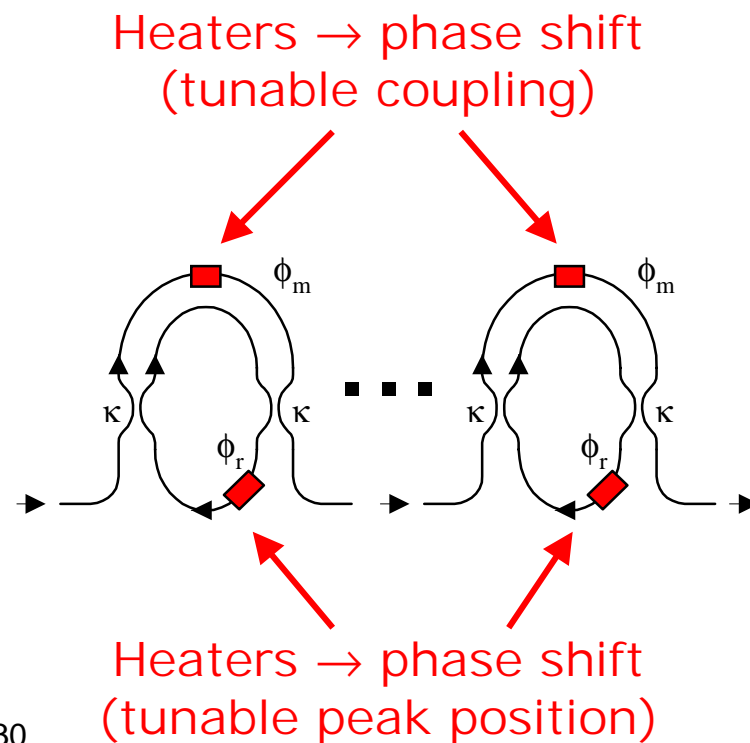
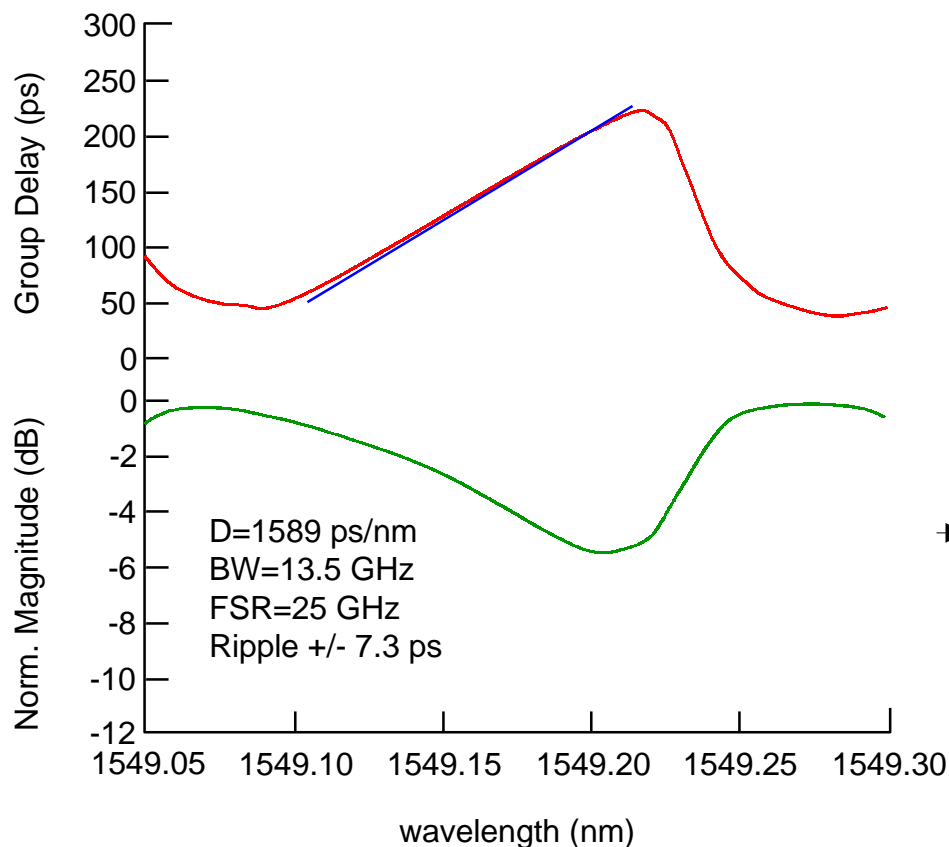


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# Four-Stage All-Pass Filter Experimental

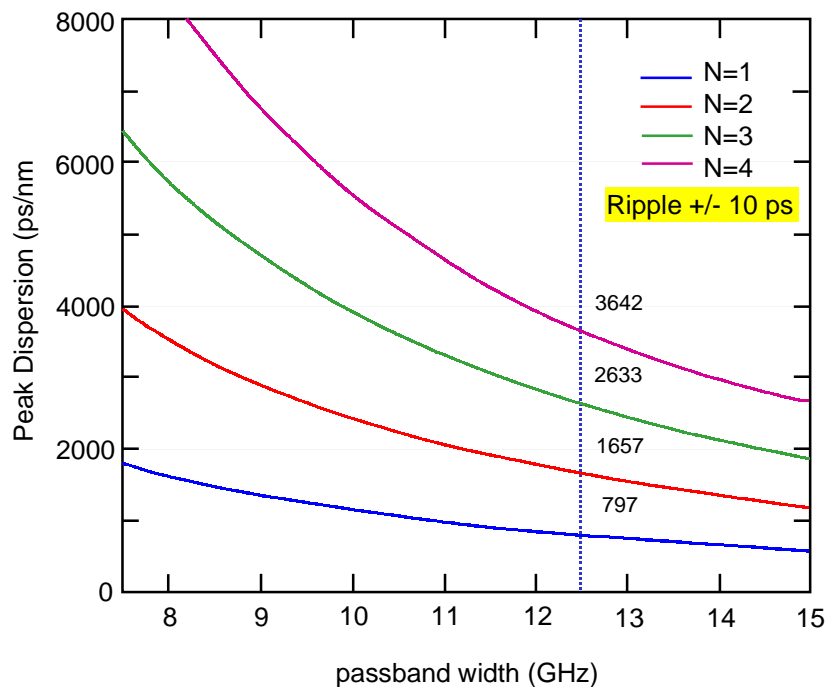


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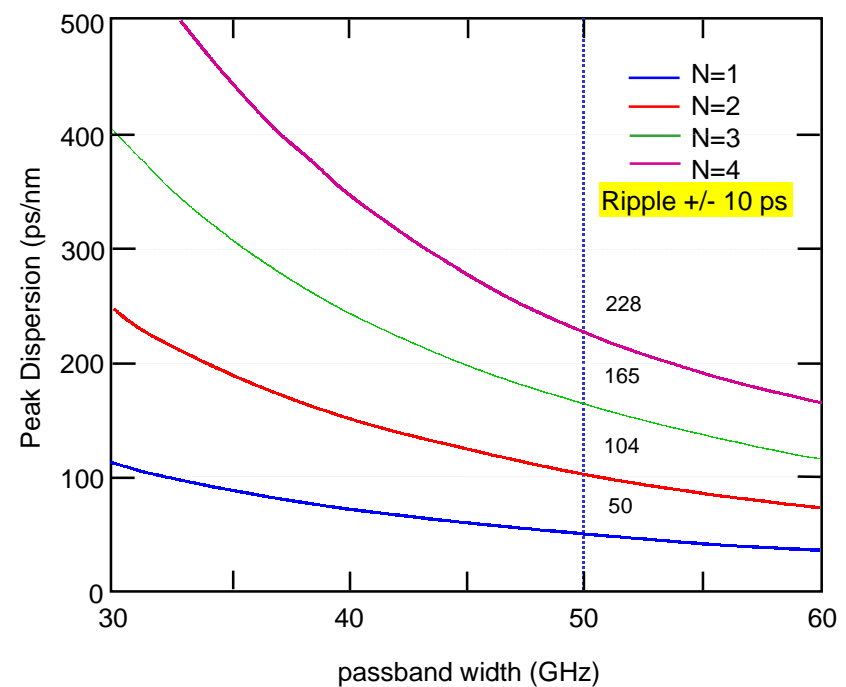
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# Dispersion vs. Bandwidth Tradeoff

## 25 GHz Channel Spacing



## 100 GHz Channel Spacing

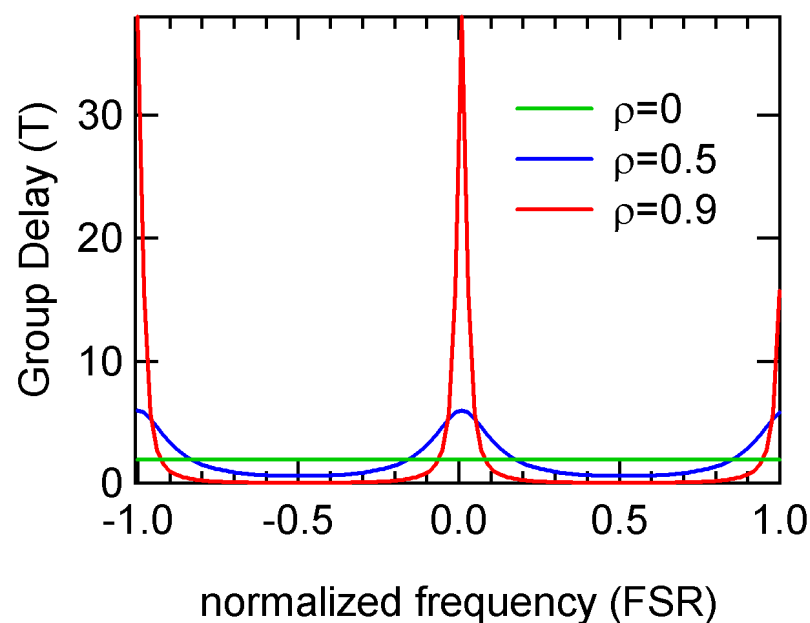
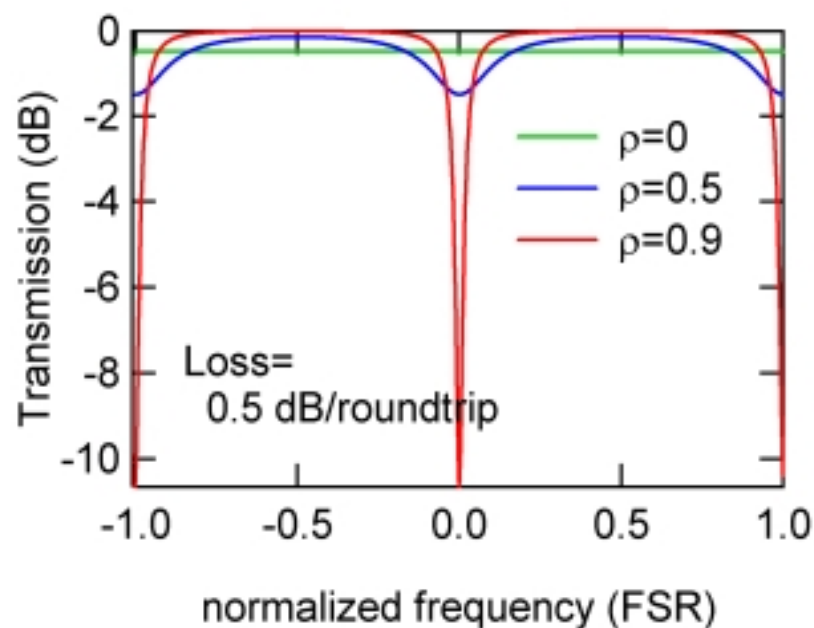


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# All-Pass Filter - Effect of Finite Loss



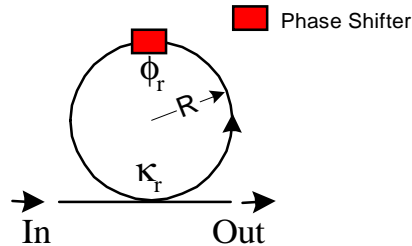
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# Broadband All-Pass Filters

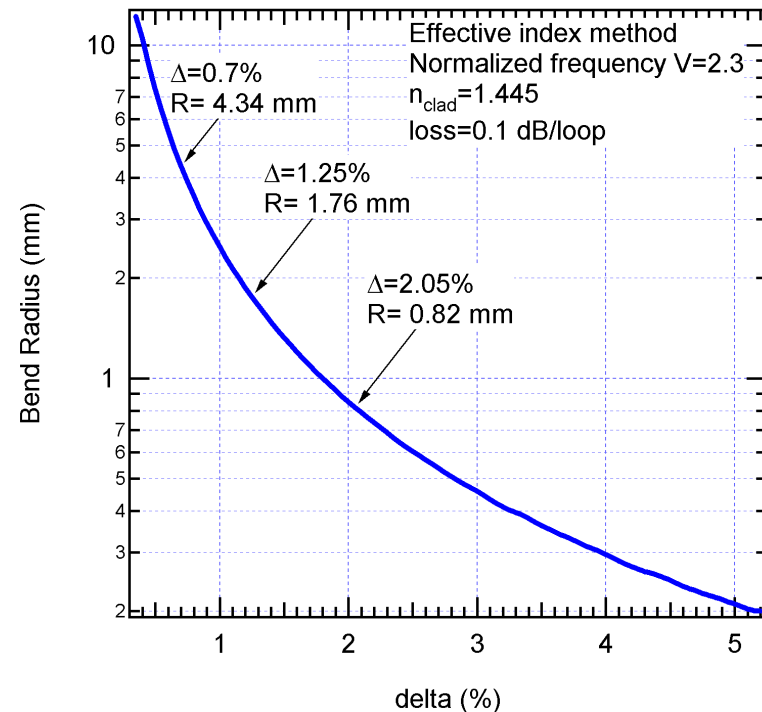
## Basic Design



$$FSR \uparrow \Rightarrow R \downarrow \Rightarrow \Delta \uparrow$$



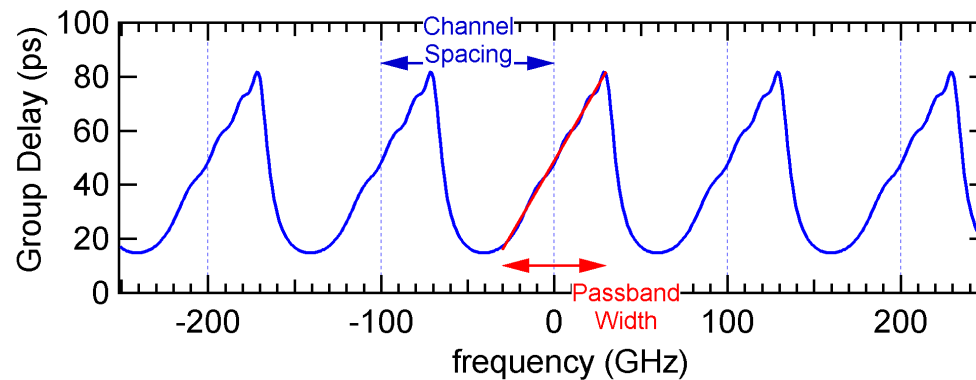
Achieving required coupling  $\kappa$   
practically not feasible



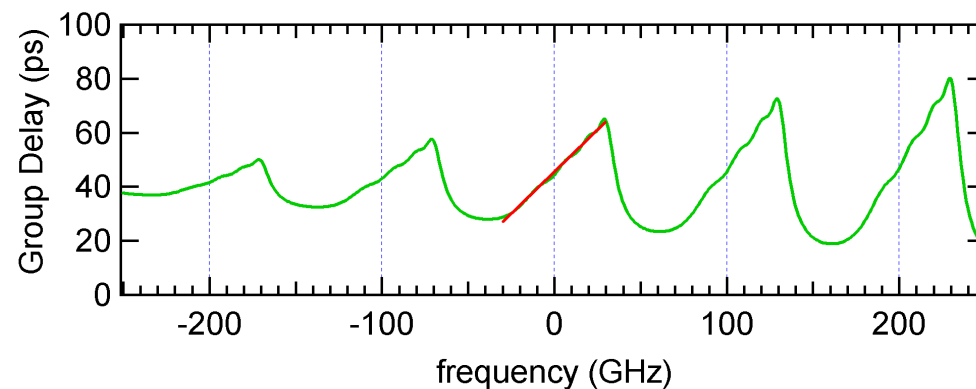
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# Multi-channel Dispersion Compensation



Constant  
dispersion  
compensation



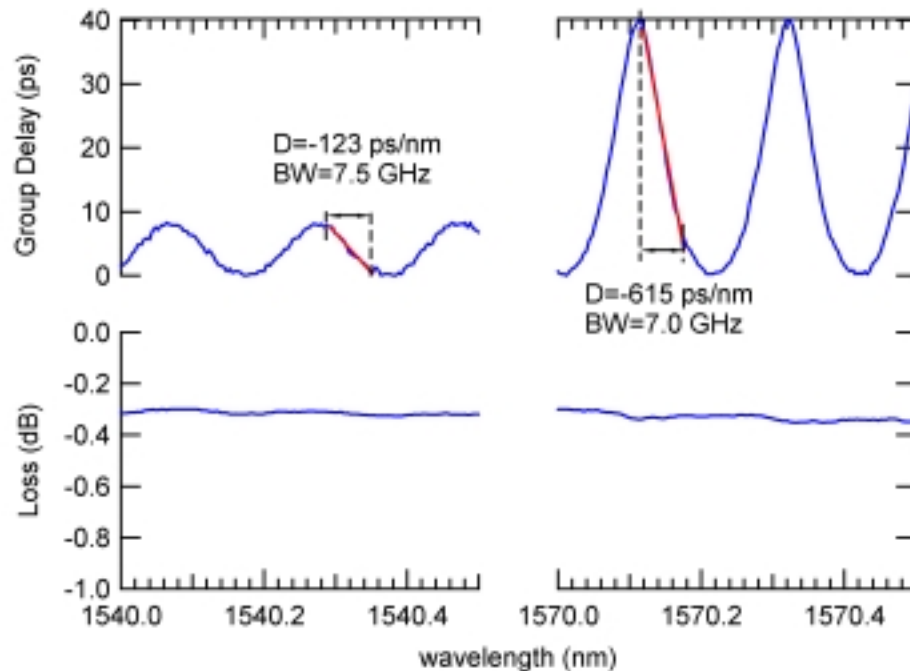
Dispersion  
slope  
compensation

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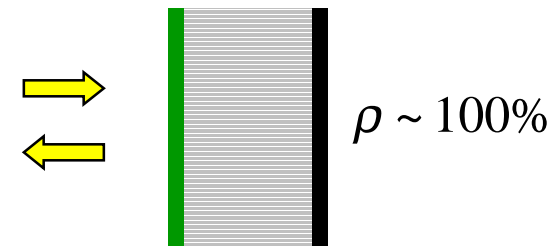
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# Thin-film All-Pass Filter

## Single-stage Silica substrate (25 GHz FSR)



Package loss 0.3 dB



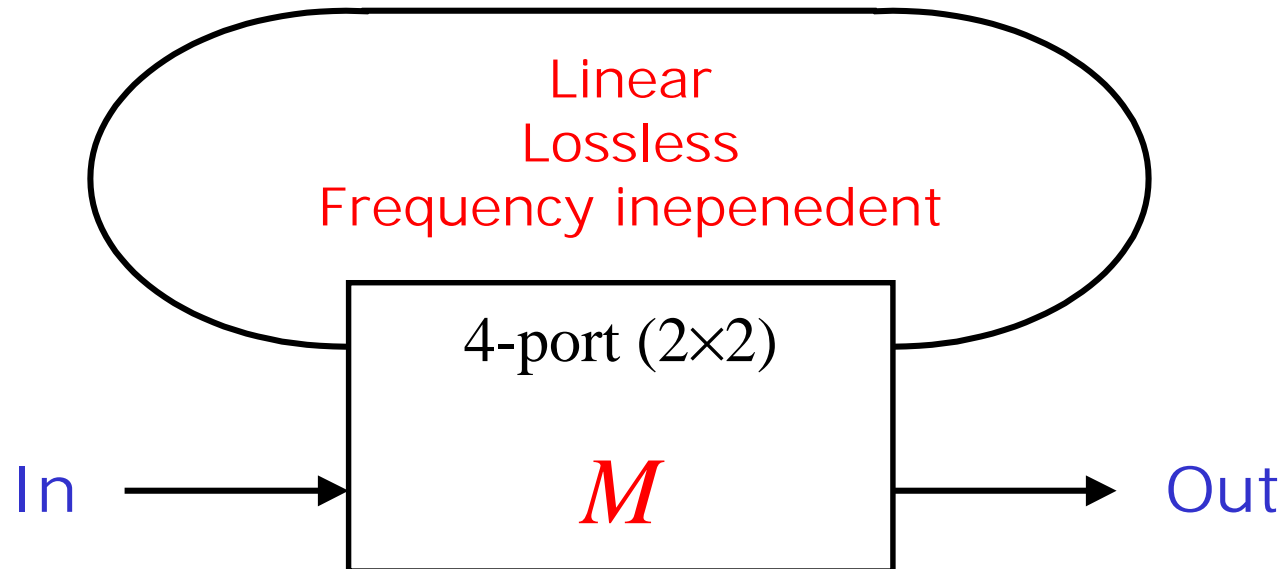
Gires-Tournois  
Interferometer (GTI)

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# General Construction of an All-Pass Filter



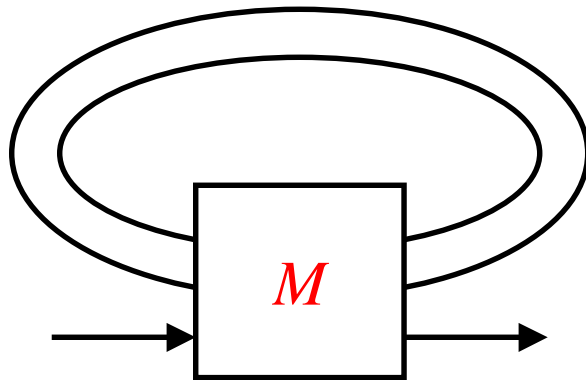
*This is an all-pass filter if:*

1.  $\det(M) = 1$
2.  $M_{22} = M_{11}^*$

FSR determined by  
feedback path delay



# More General All-Pass Structures



$$\det(M) = 1$$

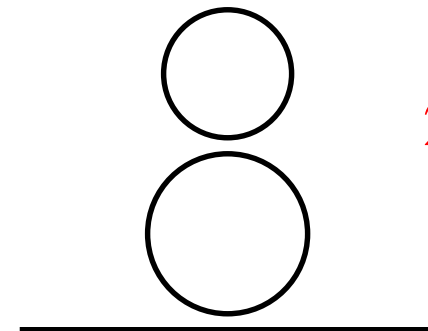
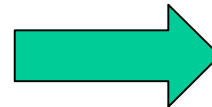
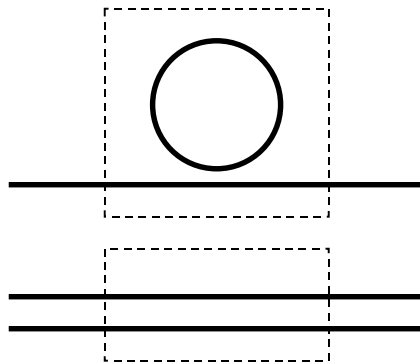
$$M_{11}^* = M_{22}M_{33} - M_{23}M_{32}$$

$$M_{22}^* = M_{11}M_{33} - M_{13}M_{31}$$

$$M_{33}^* = M_{22}M_{11} - M_{21}M_{12}$$

*Single stage  
APF*

*Coupler*



*2-stage  
APF*

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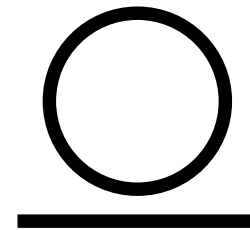


# Simple Case

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*Directional coupler*



*Single stage  
all-pass filter*

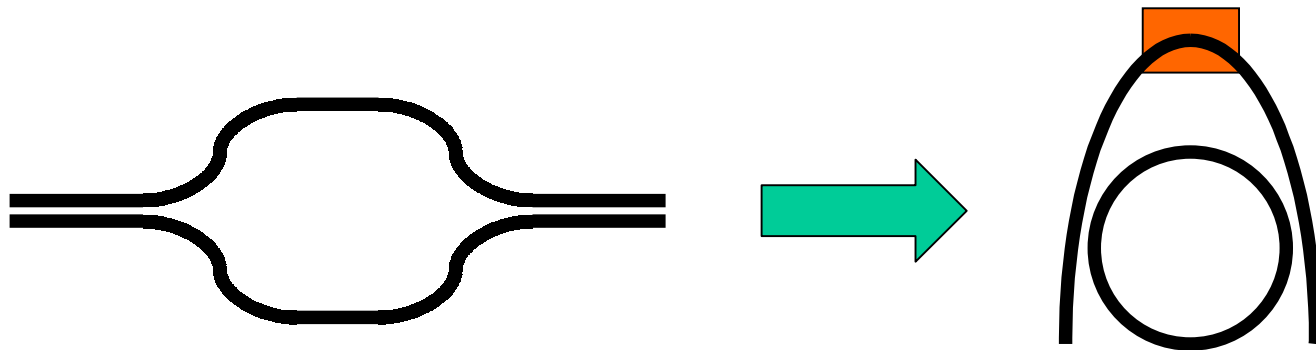
Scaling problem:



Larger FSR  $\Rightarrow$  Smaller rings  $\Rightarrow$  Larger  
bend loss  $\Rightarrow$  Larger  $\Delta$  material  $\Rightarrow$  Coupler  
gap too small



# MZI-based APF



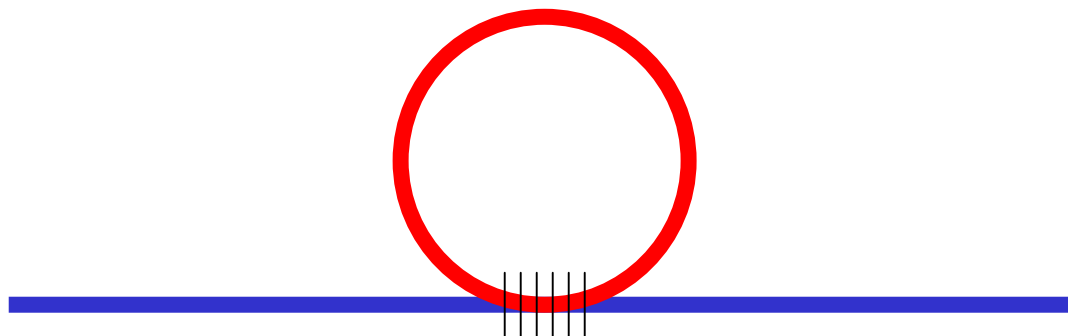
This design is no longer sensitive to the couplers

Equivalent to simple case, but with **tunable coupling**





# Another solution



*Vertical grating-assisted coupling*

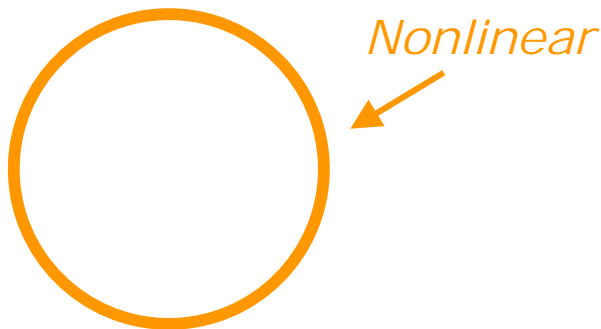


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# Nonlinear all-pass filters



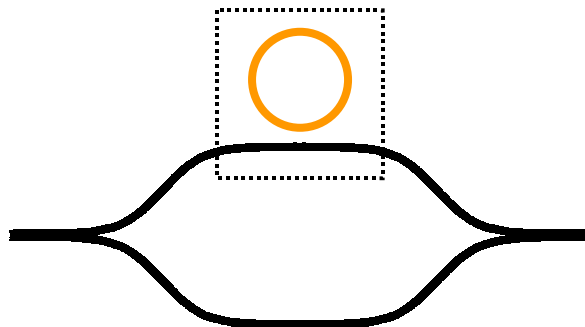
$$\Phi_{eff} \sim \left( \frac{2\pi}{\lambda} n_2 IL \right) 4F^2$$

$$F \sim \frac{\tau_{max}}{T}$$

However, large  $F$  implies  
small bandwidth



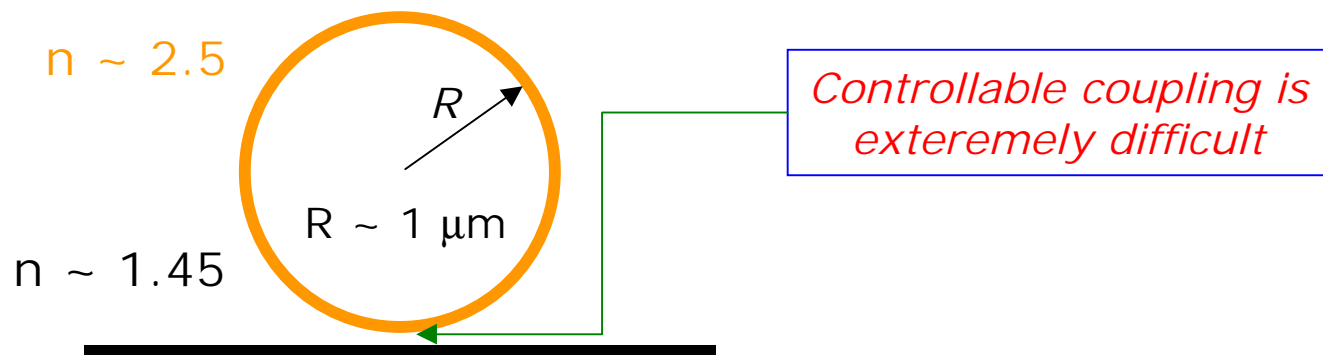
For  $\sim 1$  ps timescales  
requires very small rings  
or disks ( $\sim 1 \mu\text{m}$ )



(Heebner and Boyd, *Opt. Lett.*, 1999)

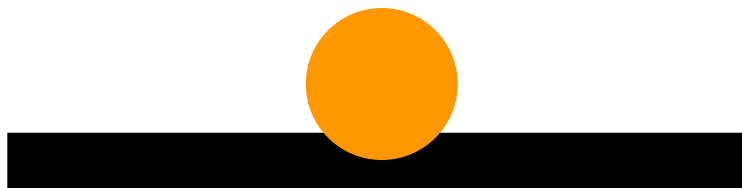


# Practical considerations



Vertical coupling

$R \sim 1 \mu\text{m}$   
 $F \sim 30$   
 Cavity losses?





# Summary

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- *Ring resonators can be used as tunable optical phase equalizers*
- *Large bandwidth devices require many small rings*
- *Ring loss needs to be minimized*
- *Nonlinear micro rings may be used for fast all-optical switching*